Norms in multilevel groundwater governance and sustainable development

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Chapter 3. Contextualizing Groundwater Problems

3.1 INTRODUCTION

“Sustainability requires human systems that are concordant at appropriate scales with the ecosystems to which they are related.” Cleveland et al. (1996: 3)

In this chapter, I elaborate upon the physical properties of groundwater resources that are relevant for this thesis, outline the natural and anthropogenic causes and consequences of groundwater change, and discuss the implications for groundwater governance. This chapter aims to answer the subsidiary question: How does an intimate knowledge of groundwater resources provide insights into how governance frameworks should be arranged? The chapter first elaborates on the natural and anthropogenic drivers/causes of groundwater change (see 3.2). Then it lays out the dominant characteristics of groundwater, namely storage, flow, pressure and quality (see 3.3). It goes on to discuss groundwater at a biophysical resources scale and the ways in which groundwater resources can be spatially delineated (see 3.4). Next, it describes the ecosystem services of groundwater (see 3.5). Then the inferences link these four elements together and discuss their implications for groundwater governance (see 3.6).

3.2 THE DRIVERS OF GROUNDWATER PROBLEMS

If not properly governed, human activity can cause or exacerbate groundwater problems through mechanisms called drivers. First I will define the term drivers as used in this research and discuss some key drivers individually based upon whether they contribute directly or indirectly to groundwater problems (Levy et al. 2012). Drivers refer to the causes of a problem and there are two types: direct and indirect drivers. Direct drivers directly affect the behavior of a local actor to engage in groundwater abstraction, contamination, or land use changes that might affect recharge. Indirect drivers influence the direct drivers and thus have an indirect effect on groundwater problems. Drivers can be distinguished from human behavior in that drivers influence the motivations behind the behavior. Section 3.2 shows the direct and indirect drivers of groundwater uses and the geographic levels at which they occur.

3.2.1 Direct Drivers

There are two direct drivers that are also overlying in that they might affect the degree to which other drivers manifest themselves. The first is the presence or absence of infrastructure and the second is asymmetrical access to or demand for groundwater.

Infrastructure is considered overlying because, in most cases, groundwater cannot be accessed without it. Further, the presence or lack of other types of infrastructure may influence the use of groundwater or increase potential contamination of groundwater (Crosgrove and Cosgrove 2012; Gupta and Pahl-Wostl 2013). The absence of piped, municipal water or water for irrigation supply may drive users to install their own wells (Shah 2009). Further, poorly constructed sanitation systems located in recharge areas can result in groundwater contamination. Since groundwater infrastructure is mostly local, infrastructure is predominantly a subnational issue. Yet, the Disi transboundary aquifer and the Botswanan portions of the STAS are examples of groundwater infrastructure being a transboundary and national-level driver, respectively (see 6.2.2 on the Al-Saq/Al-Disi Transboundary Aquifer and Chapter 8 on the STAS).

In terms of asymmetrical access or demand, users with drastically differing needs for groundwater or with different levels of access can trigger a ‘pumping race’ wherein groundwater is overused in the present because availability might be limited in the future (Hoogesteger and Wester 2015). Property rights may also affect access when private land ownership or other forms of land tenure allow owners to
### Table 3.1 Drivers of groundwater problems at multiple geographic levels

<table>
<thead>
<tr>
<th>Drivers</th>
<th>Global</th>
<th>Regional-TB</th>
<th>National</th>
<th>Sub-national</th>
<th>Key References</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DIRECT</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Individuals, household, and subsistence needs resulting in pumping and pollution</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td>Braune and Adams 2013; Jarvis et al; 2005; Shah 2009; Moench 2003</td>
</tr>
<tr>
<td>Services provision by local authorities resulting in pumping and pollution</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td>Braune and Adams 2013; Moench 2003; Jarvis et al. 2005</td>
</tr>
<tr>
<td>Small-scale and commercial agriculture resulting in pumping and pollution</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td>Braune and Adams 2013; Siebert et al. 2011; Hoogesteger and Wester 2015</td>
</tr>
<tr>
<td>Pumping and pollution by industry (e.g., manufacturing, energy, mining, bottled water)</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td>Braune and Adams 2013; Crossgrove et al 2012; Gupta and Pahl-Wostl 2013; Dore et al. 2012; Söderbaum and Tortajada 2011; van der Gun et al. 2012; Moench 2007</td>
</tr>
<tr>
<td>Land use strategies of different actors and how it affects recharge</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td>Braune and Adams 2013; Foley et al. 2005; Betelaan et al 2003; Rajan et al. 2006</td>
</tr>
<tr>
<td>Natural changes in available water quality (e.g., drought or flood)</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td>Taylor et al 2005; van Steenbergen 2006</td>
</tr>
<tr>
<td><strong>INDIRECT</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Climate change</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>Gupta and Pahl-Wostl 2013; Vrba et al. 2006; Taylor et al. 2005</td>
</tr>
<tr>
<td>Culture affecting access rights and pollution behavior</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Crosgrove et al 2012; Cullet and Gupta 2009; Sophocleus 2000</td>
</tr>
<tr>
<td>Demography (population growth and migration and how this affects groundwater access)</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>Crosgrove et al 2012; Gupta and Pahl-Wostl 2013; Dore et al. 2012; Hoff 2009</td>
</tr>
<tr>
<td>Economy (the focus on economic growth without taking water limits into account)</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td>Gupta and Pahl-Wostl 2013; Hoff 2009; Söderbaum and Tortajada 2011</td>
</tr>
<tr>
<td>International trade (e.g., ‘globalization’ or trade in virtual water)</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td>Gupta and Pahl-Wostl 2013; Hoff 2009; Söderbaum and Tortajada 2011</td>
</tr>
<tr>
<td>Non-groundwater policies on agriculture, manufacturing, mining, energy, spatial issues, trade, and economic growth</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td>Braune and Adams 2013; Gupta and Pahl-Wostl 2013; Hoff 2009; Sebastian and Warner 2013</td>
</tr>
<tr>
<td>Culture affecting access rights and pollution behavior</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td>Foster and Chilton 2003; Foster and Garduño 2013; Shah et al. 2012</td>
</tr>
<tr>
<td>Political dynamics between states</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td>Zeitoun et al. 2009; Zeitoun and Warner 2006</td>
</tr>
<tr>
<td>Poverty</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td>Braune and Adams 2013; Moench 2003; Sebastian and Warner 2013</td>
</tr>
<tr>
<td>Technology</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td>Crosgrove et al 2012; Gupta and Pahl-Wostl 2013; Söderbaum and Tortajada 2011</td>
</tr>
</tbody>
</table>

a references drivers specifically
b reference causes generally
c references groundwater specifically
d references water generally
e references ‘attitudes’ or ‘beliefs’
“capture” groundwater so long as it is flowing under the land – known as the “rule of capture.” For example, household users may pump and store groundwater if they fear agricultural uses will deplete the resource (Braune and Adams 2013); nearby property owners or even neighboring countries may try to out-pump each other in the absence of an agreed upon allocation regime (Jarvis et al. 2005). As such, this driver can occur at both transboundary and subnational levels and has significant implications for sustainability and inclusivity.

Two drivers fit under the broad umbrella of fulfilling municipal or rural water supply and sanitation services: household uses (drinking water, sanitation and hygiene) and subsistence agriculture. While the volumes of these uses are relatively small compared to industrial uses, they still constitute important drivers. They can contribute to poverty eradication (Moench 2003), on the one hand, and to the cumulative problems of overexploitation and contamination (e.g. Braune and Adams 2013 with respect to Sub-Saharan Africa) with respect to Sub-Saharan Africa, on the other. Since transboundary or local groundwater resources may supply users, this driver is relevant across all these levels.

National industries as well as the trade in products produced by those industries are key drivers of groundwater problems (Gupta and Pahl-Wostl 2013; Söderbaum and Tortajada 2011). National industries relying upon groundwater might include commercial agriculture and large-scale animal husbandry (Crosgrove and Cosgrove 2012; Dore et al. 2012); mineral extraction including petroleum (Braune and Adams 2013); production of geothermal energy (Margat and van der Gun 2013); and see Box 3.1 below r.e. production of bottled water and beverages (Rodwan 2015). National industry is relevant at the transboundary level and below while international trade is also relevant at the global level.

**Box 3.1 Corporate Privatization’s Role in Industry-Driven Groundwater Use**

Since 2000, scholars as well as environmental justice and human rights activists have drawn increasing attention to the food and beverage industries’ large-volume groundwater abstractions. Notable instances of depletion have occurred in the US (Nestlé in Michigan – see Bednarz 2007) and India (Uttar Pradesh – see Drew 2008; Ghoshray 2006; Hills and Welford 2005; Coca-Cola in Rajasthan - see Karnani 2014) as well as salinization in Tanzania (SABMiller – see Alter 2009). Others attempts at privatization have been deterred due to public outcry (see Glennon and Rogers 2007 r.e. bottled water in Wisconsin). In each of these cases, local, state and federal laws regarding (ground)water rights have been structured in such a way that companies that either purchase land overlying groundwater resources or drill a well for the purpose of ‘beneficial use’ (i.e. enhancing the local economy via industry) have unlimited rights to pump groundwater. In the case of the US, some of the rights regimes were developed before clear understandings of the relationship between surface and groundwater, or they were only designed to protect navigation and not environmental integrity (see Bednarz 2007). Nevertheless, in exercising these rights, companies have been able to pump groundwater at a rate of roughly 1,000 liters per minute eventually reducing flows to related ecosystems and often effecting the availability of public water supplies.

Land grabbing - defined as “acquisitions or concessions that are one or more of the following: (i) in violation of human rights, particularly the equal rights of women; (ii) not based on free, prior and informed consent of the affected land-users; (iii) not based on a thorough assessment, or are in disregard of social, economic and environmental impacts, including the way they are gendered; (iv) not based on transparent contracts that specify clear and binding commitments about activities, employment and benefits sharing, and; (v) not based on effective democratic planning, independent oversight and meaningful participation” (International Land Coalition 2011 Tirana Declaration: Article 4) – has also become synonymous with (ground)water grabbing (see generally Rulli et al. 2013). As of 2013, land grabbing affected at least 62 countries on all continents except Antarctica with over 145 billion cubic meters grabbed (Rulli et al. 2013: 893). According to Pearce et al. (2012), groundwater depletion often constitutes water grabbing from future generations.

Not all drivers of groundwater problems are solely anthropogenic. Anthropogenic activity can shift the groundwater resources out of their natural equilibrium and result in permanent depletion or contamination (see 3.3). Natural changes in available water quality and quantity can occur because of climatic or tectonic shifts. Climatic shifts such as increased frequency or duration of droughts and floods can have several consequences for groundwater. First, drought may result in reduced recharge and lowered groundwater tables (Peters et al. 2005; Villholth et al. 2013). Further, it can result in salinization of groundwater resources and...
put certain areas at risk from mobilization of arsenic or fluoride (Taylor et al. 2013; van Steenbergen 2006). With respect to tectonic movements, earthquakes can lead to groundwater level variations or create hydraulic connection between two resources that were not previously connected and might open up a formerly potable resource to contamination (Claesson et al. 2004; Malakootian and Nouri 2010), even affecting the microbiota therein (Galassi et al. 2014). Also, a resource that previously yielded substantial volumes of groundwater may no longer do so as a result of the geology becoming fractured or split (Rojstaczer and Wolf 1992).

### 3.2.2 Indirect Drivers

A key group of indirect drivers includes non-groundwater policies and scientific/technological advances occurring at all geographic levels. At the global level, such drivers include development policies such as the human right to water, the MDGs (through 2015), and SDGs (post-2015) having the potential to affect regional-transboundary and national law and policies (Crosgrove and Cosgrove 2012). The regional and national levels also include non-groundwater policies regarding surface water use (potentially conjunctive use), agriculture and food security, trade, land use and land tenure and economic development (Foster and Chilton 2003; Foster and Garduño 2012; Shah et al. 2012). In particular, the goal of poverty eradication has the potential to increase access to, and utilization of, groundwater resources (Braune and Adams 2013; Moench 2003). It can also drive economic activities that could result in unsustainable (ground)water use (Sebastian and Warner 2013). Similar to poverty eradication, the goal of economic development may also result in land use changes that can reduce groundwater recharge or have the potential to contaminate groundwater (Braune and Adams 2013; Gupta and Pahl-Wostl 2013; Hoff 2009; Sebastian and Warner 2013).

Technology facilitates agricultural intensification and enhances the users’ ability to drill deeper wells, indirectly driving groundwater use (Crosgrove and Cosgrove 2012; Gupta and Pahl-Wostl 2013; Söderbaum and Tortajada 2011). Political dynamics can hinder joint groundwater governance between states and potentially exacerbate the direct driver of asymmetrical access or demand (Zeitoun et al. 2009; Zeitoun and Warner 2006).

Cultural and demographic shifts can also be indirect drivers of groundwater problems. Attitudes regarding access and allocation, wasteful use of resources, and public responsibility regarding environmental quality can result in behaviors that drive excessive use or contamination (Crosgrove and Cosgrove 2012; Cullet and Gupta 2009; Sophocleous 2000). Cultural attitudes are considered to be primarily national in character although they may have a regional dimension as well. Demographic shifts such as migration, population growth and localized increases in population density via urbanization can occur at all geographic levels and add stress to groundwater resources by increased withdrawals(Crosgrove and Cosgrove 2012; Dore et al. 2012; Gupta and Pahl-Wostl 2013; Hoff 2009).

Climate change, ‘the economy,’ and international trade are indirect drivers that are most difficult to grasp as they both operate across all geographic levels and are extremely complex in origin and consequence. The effects of climate change on groundwater have been discussed in Section 1.2 and were shown to potentially affect available groundwater volumes and groundwater quality (Girman et al. 2007; Gupta and Pahl-Wostl 2013; Taylor et al. 2013). Further, human behavior might shift or adapt in anticipation of these effects, ideally resulting in conservation but potentially resulting in overuse. With regard to the economy and trade, distortion of markets and demands for groundwater-intensive products can occur through subsidies as well as preferential or ‘free-market’ trade regimes. These can indirectly drive groundwater problems if they boost demand and production in the agriculture and extractive industries, particularly if these demands are the result of market distortions or exclusion of environmental costs in pricing (Crosgrove and Cosgrove 2012; Gupta and Pahl-Wostl 2013; Hoff 2009; Söderbaum and Tortajada 2011).
3.3 **GROUNDWATER’S PHYSICAL CHARACTERISTICS**

A broad definition of groundwater is water that has completely saturated the openings (fissures and/or pores) of the earth’s subsurface geological formations (Fitts 2002). Groundwater is distinct from water in the subsurface more generally, in that it excludes water in partially saturated soil. In many places, groundwater is just beneath the land surface and in others it is far below, out of the reach of even the most advanced drilling technologies. Groundwater in its natural state has three origins: meteoric origins from participating in the hydrologic cycle (Chilton 1996; Conners 2013; Margat and van der Gun 2013); connate origins from being trapped deep below land or sea surface during marine sedimentation (Chilton 1996; Meinzer 1923); or magmatic origins from steam being captured in magma during volcanic activity. Groundwater formed through the latter two of these processes has little interaction with the hydrological cycle. However, by way of geological or human-induced activities, these types of groundwater may mix and/or become part of the hydrological cycle when they previously were not. For example, deep groundwater originating from volcanic activity could be pumped to land surface and discharged into a river. Groundwater resources have four dominant natural characteristics: storage (i.e. volume of groundwater), flow, pressure, and quality. They are discussed individually here, although in reality, they are all closely linked. As such, these relationships are highlighted briefly after the individual descriptions.

### 3.3.1 Storage

For groundwater, storage is its dominant property, whereas flow is dominant for surface water (Foster, Chilton, et al. 2013). Groundwater storage volumes significantly exceed those of surface water and serve as a critical buffer to climate variability since these volumes are less likely to shift as a result of variations in rainfall or other climatic factors. Different types of geological formations have different potential for storage. Alluvial formations that were created as a result of sedimentation from rivers typically have the highest ability to store groundwater, are the most easily exploited and replenished as they often have a hydrological relationship to a surface water body. Hard rock formations originating from volcanic activity typically have much lower storage volumes because the very slow geological process of weathering must occur in order to open up space for groundwater to be stored. Thus, formations created as a result of volcanic activity, such as small islands, are much less likely to have large groundwater reserves available to them – noting that the older and/or larger the island is, the more groundwater resources are likely available.

### 3.3.2 Flow

Flow is also a key property of groundwater. While a relatively small proportion of groundwater actively participates in the hydrological cycle compared to its total volume (Foster, Chilton, et al. 2013; Gleeson et al. 2012), these volumes are significant, being over three times that of surface water (Gleeson et al. 2015). In most situations, groundwater has a low flow velocity, moving between 0.01m and 10m per day (Foster, Chilton, et al. 2013). Therefore, groundwater residence times (i.e. amount of time spent in storage) can range from decades to millennia under natural conditions. Flow direction and velocity are key factors (in combination with storage) in determining how quickly groundwater might be replenished at a particular location and/or how quickly groundwater contamination might spread. Direction and velocity are determined by gravity (e.g. the slope of a particular geological formation) and the degree to which groundwater is flowing through open or connected spaces. For example, alluvial formations are relatively well connected and would replenish or contaminate quickly while volcanic formations would replenish slowly and likely only have localized contamination.

### 3.3.3 Pressure

Another key feature of groundwater is pressure. Groundwater contained within a geological formation exerts pressure upon this formation and to some extent stabilizes it. If groundwater is removed, the pressure reduces resulting in compaction of the formation. Depending on the formation and degree of dewatering this process
can be irreversible and permanently decrease the groundwater storage capacity of the formation. The process of compaction of the formation can also cause the land to sink, also called subsidence, resulting in damages to infrastructure and habitat (Domenico and Schwartz 1998). In coastal areas, abstraction of fresh groundwater can result in salt water intrusion because seawater will enter the geologic formation due to reduced pressure from fresh water (Margat and van der Gun 2013). Another key feature related to pressure is that it is one of the distinguishing characteristics of unconfined and confined portions or layers of groundwater resources. The unconfined portions or layers are those into which water seeps from the ground surface directly into the resource. To access this groundwater, it must be pumped up to the surface as there is no natural pressure. Confined portions or layers that are overlain by an impermeable layer prevents water from seeping into the groundwater resource from the ground surface located directly above. Instead, water seeps in from further away where the impermeable layer does not exist. Because of its impermeable cover, this groundwater is under pressure. When a well is drilled in a confined portion or layer, the pressure is relieved and the water level rises in the borehole to a level above the height of the layer where the groundwater is stored (Nonner 2010). This is called artesian groundwater and artesian wells. In some cases, the pressure in the confined portion or layer may be so high that the water level rises even above ground surface. Such boreholes are called flowing artesian wells. Artesian wells have the benefit that they require less or in case of flowing artesian wells even no energy to access groundwater, but they pose a specific groundwater management challenge to avoid wasting of groundwater and unnecessary depletion of the resource.

### 3.3.4 Quality

Geogenic contamination (i.e. contamination that originates from geological processes as opposed to human activity) limits the potential for groundwater to meet basic human needs in many locations (see 1.2). Arsenic and fluoride compounds are often imbedded in the geology of certain aquifers. In certain areas, arsenic is contained in the rock formations storing groundwater. Several natural characteristics of the subsurface environment such as temperature, acidity, presence of sulfur and metal oxides, and velocity of groundwater flow can affect arsenic mobility. Human activities that increase acidity such as mining, or change groundwater flow patterns such as pumping, can also increase arsenic mobilization (Tuinhof et al. 2006). Continental rifts, margins and islands that have volcanic geology can have high concentrations of fluorine. Acidic groundwater and groundwater with long residence times, especially in deep aquifers, can mobilize fluoride (Feenstra et al. 2007).

Saline groundwater has two origins: meteoric and connate. Saline groundwater of meteoric origin often occurs in arid and semi-arid areas where there is insufficient rainfall to recharge the aquifer for long periods of time, so salts collect in the solid. Then during major rainfall events, they are recharged along with surface water. Connate groundwater is very old sea water that was trapped in deep aquifers as a result of tectonic processes like the shifting of continental plates (Weert et al. 2009). Fresh groundwater can become naturally salinized through saline intrusion. Saline intrusion is often human induced but can also occur as a result of rising sea levels and/or natural reductions in groundwater pressure in coastal areas due to geological shifts. The transboundary aquifers and countries with geogenic contaminants are shown in Map 1.3 and Map 1.5. The maps indicate that coastal, semi-arid and arid environments tend to be susceptible to salinity problems, while fluoride and arsenic risk appear to have a more random spatial distribution as a result of it being associated with faulting. However, these two types of risk are closely related to local and regional geology (see 1.2). Nevertheless, most countries, with the exception of those in Central Africa, Northern Europe and Western Asia and a few others are affected by more than one type of geogenic contamination.

### 3.3.5 Drivers and Groundwater Characteristics

This subsection highlights how the drivers that result in groundwater pumping can affect one or more of the four key groundwater characteristics just discussed. Under ‘steady state’ or equilibrium conditions - when
there are no outside disturbances - groundwater recharge will always equal groundwater discharge over the long-term, even if this is hundreds or thousands of years. However, abstraction from wells can (1) induce recharge by pulling water into a well more quickly than it would normally recharge and/or (2) reduce natural discharge or pulling water away from where it would normally discharge. Pumping can also affect groundwater levels by creating a ‘cone of depression.’ For example, a well drilled to 20 meters’ depth in areas where the groundwater level is 10 meters deep will eventually pull groundwater downwards towards the bottom of the well and nearby groundwater levels will drop (see Figure 3.1). This drop may cause nearby, shallower wells to become dry. Should the well pump beyond the amount recharged, there would be lack of water pressure in the pore space the groundwater previously occupied and permanent depletion would occur. Over pumping can also trigger the release of geogenic contaminants, such that when and if groundwater is recharged it is of degraded quality. In locations with fossil groundwater, where there is no meaningful recharge on a human time-scale, any extraction is synonymous with a permanent depletion of resources and is referred to as ‘groundwater mining’ (Foster and Loucks 2006; Gleeson et al. 2012). From this brief description, it is clear that issues of groundwater storage, flow, pressure and quality are intimately linked.

Figure 3.1 Effects of Groundwater Pumping

Source: Altaner, 2012

3.4 **GROUNDWATER AT A BIOPHYSICAL SCALE: DEFINING GROUNDWATER UNITS**

There are six types of spatial units to delineate groundwater resources: (1) groundwater basins (WHYMAP 2008); (2) global groundwater regions (International Groundwater Resources Assessment Centre 2004); (3) groundwater provinces (Meinzer 1923); (4) aquifers (Arago 1834); (5) groundwater bodies (European Parliament 2000); and (6) groundwater flow systems (Toth 1963). Groundwater basins, regions and provinces will only be discussed briefly as they are not used in any known governance texts, possibly because their geographic areas are considered too large for sufficiently tailored governance and management frameworks. Aquifers, groundwater bodies and groundwater flow systems are co-existing and sometimes competing conceptualizations of groundwater resource units in that they emphasize different attributes of the resource in their application. Aquifers focus on the structure of the geological formation; groundwater bodies on the relationship between the hydrogeological and administrative scales; and groundwater flow systems on how groundwater moves in the subsurface.
3.4.1 Groundwater Basins, Regions and Provinces

The German Geologic Survey (BGR) has mapped groundwater basins based on the characteristics of the geological formations and their recharge potential (WHYMAP 2008). Alluvial formations have the highest potential for storage and flow (see 3.2) and are thus considered ‘major groundwater basins.’ If these formations have been highly altered by geologic activity, impeding storage or flow, they are considered ‘complex’. Volcanic or other hard rock formations that have been weathered are considered ‘local and shallow’ (see Map 3.1). IGRAC (2004) has identified 36 groundwater regions according to dominant hydrogeological features and ‘overall groundwater setting’. They can be roughly divided into four groups: basement regions, which are shallow with limited groundwater storage; sedimentary basin regions, which can go to considerable depth and potentially form large reservoirs; high-relief folded mountain regions, where groundwater occurs sporadically at varying depth but can yield good quantity water; and volcanic regions where only specific areas are capable of transmitting groundwater (van der Gun et al. 2011). The BGR groundwater basins and IGRAC regional aquifers are overlain in Map 3.1 showing that these groundwater regions primarily coincide with alluvial basins as key groundwater reserves. Groundwater provinces – first conceived by Oscar Meinzer (1923) - can be seen as a subdivision of these groundwater regions and are one sixth of their size on average. There are 217 groundwater provinces, which possess more homogeneous characteristics than the regions and represent ‘geographical zones.’

3.4.2 Aquifers

The aquifer concept is widely adopted by hydrogeologists globally as the preferred unit for assessment and management. It has also gained significant traction in the legal and social sciences as the preferred unit of governance. However, there is no agreed upon definition of an aquifer used across fields (see Box 3.2).

<table>
<thead>
<tr>
<th>HYDROGEOLOGICAL DEFINITIONS</th>
<th>LEGAL AND SOCIAL SCIENCES DEFINITIONS</th>
</tr>
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<tbody>
<tr>
<td>A saturated permeable geological unit that can transmit significant quantities of water under ordinary hydraulic gradients (Freeze and Cherry 1979).</td>
<td>A subsurface layer or layers of rock or other geological strata of sufficient porosity and permeability to allow either a significant flow of groundwater or the abstraction of significant quantities of groundwater (European Parliament 2000).</td>
</tr>
<tr>
<td>A saturated bed, formation or group of formations which yields water in sufficient quantity to be of consequence as a source of supply (Walton 1970).</td>
<td>A permeable water-bearing geological formation underlain by a less permeable layer and the water contained in the saturated zone of the formation (ILC Draft Articles 2008).</td>
</tr>
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</table>

In this thesis, I define aquifers as underground geological formations that are permeable, saturated and water-bearing (Domenico and Schwartz 1998; Freeze and Cherry 1979; adapted from Walton 1970). A less permeable layer also underlies them. Aquifers are hydrologically contiguous and are adjacent, horizontally and vertically, to geological formations that either do not contain groundwater (unsaturated zones) or are not capable of transmitting groundwater in significant quantities (aquitards and aquicludes). Aquifers range in areal extent from a less than ten to more than a million square kilometers and range in thickness from a few to thousands of meters. They can exist as an isolated single unit, but are often hydraulically connected to other aquifers - horizontally or vertically - forming aquifer systems. A single system may include multiple types of aquifers.

Two main types of aquifers are commonly referenced: unconfined and confined. There are also semi-confined and perched aquifers. Each of these types may or may not receive contemporary recharge from meteoric waters. If an aquifer does not receive such recharge, it is considered to contain ‘fossil groundwater.’ However, in this research, the word ‘type’ is regarded as a misnomer. In general, typologies are fixed. The ‘types’ assigned to aquifers are often relative rather than fixed and depend on how the boundaries of the aquifer are delineated. Recharging confined aquifers provide a good example. Confined aquifers are portions of the formation that are overlain by a low-permeability layer, which prevents recharge from entering the
map 3.1 major groundwater basins and regional aquifer systems
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aquifer vertically from above (Fitts 2002; Margat and van der Gun 2013). Nevertheless, these aquifers can be recharged horizontally through a hydrologically connected unconfined aquifer. In unconfined aquifers, groundwater is in direct contact with the atmosphere and can be recharged by water percolating through soil pores (Fitts 2002; Margat and van der Gun 2013).

These two types of aquifers are then distinguished through delineation and depending on the purpose of the delineation, it may divide the aquifer’s confined area and unconfined area, making distinct unconfined and confined aquifers; or it may include both confined and unconfined areas, making the aquifer semi-confined (see Figure 3.2). Therefore, this thesis will reference unconfined and confined areas of aquifers when this is the most appropriate hydrogeological characterization. In contrast, perched aquifers are localized, shallow pockets of water surrounded by non-water bearing geological formations and are much more fixed in their conceptualization. These aquifers are particularly important resources on small islands where they may compose a significant amount of the available, fresh groundwater.

Figure 3.2 Stylized Image of Confined and Unconfined Aquifer

This discussion demonstrates that the conceptualization of aquifers and aquifer systems is rather subjective. First, defining the boundaries of an aquifer is a function of data availability, technique, approach, training and perhaps even tradition. One hydrogeologist may identify an aquifer system and the other might identify a single aquifer. One hydrogeologist may draw the aquifer boundaries stopping at the confined portion of the aquifer while another may expand the boundary to include the recharge area – making it semi-confined.

Thus, aquifer delineation is an output of spatial knowledge construction generated through specific processes involving specific actors (see Baud et al. 2014) - typically hydrogeologists but also potentially politicians and policy makers. Further, the delineation and definition of the aquifer plays a critical role in determining the governance framework necessary for its sustainability.

3.4.3 Groundwater Bodies

The European Union (EU) refers to ‘groundwater bodies’ for monitoring and managing the qualitative and quantitative status of groundwater and attaining ‘good quantitative and qualitative status’ for all groundwater bodies by 2015. The EU Water Framework Directive (WFD: Art. 3) defines a body of groundwater (a.k.a. groundwater body) as “a distinct volume of groundwater within an aquifer or aquifers,” which can be domestic or transboundary. However, groundwater bodies are management units, not necessarily hydrologic units - aquifers can be divided into groundwater bodies or groundwater bodies can contain multiple aquifers (see Map 3.2).
Map 3.2 Types of Groundwater Units Used in the European Union

**Legend**

- Transboundary Aquifers*
- Transboundary Groundwater Bodies^
- Recharge in Groundwater Basins~
- Local and Shallow Aquifers
  - ≤100 mm/a
  - >100 mm/a
- Complex Geologic Structures
  - ≤300 mm/a
  - >300 mm/a
- Major Groundwater Basin
  - ≤200 mm/a
  - >300 mm/a

* Delineated according to information from the GEF Transboundary Waters Assessment Programme and the GEF Dinaric Karst Transboundary Aquifer System Project, available in the IGAC GIS (IGAC 2016).
^ Delineated according to the EU Water Framework Directive (EU WISE 2016). Note, some groundwater bodies stop at borders because of country decisions, not necessarily hydrogeology.
~ Delineated according to WHYMAP (BGR 2008). "Major groundwater basin" refers to groundwater resources stored in large alluvial formations with high potential for storage and flow and that provide good conditions for groundwater abstraction; "complex hydrogeologic structures" refer to highly productive groundwater resources in areas that have been highly altered by geologic activity; "local and shallow aquifers" refer to areas with limited groundwater productivity.
3.4.4 **Groundwater Flow Systems**

In 1963, József Tóth (1963) undertook the delineation of ‘groundwater flow systems.’ He argued that groundwater systems have dynamic and changing boundaries and are nested going from local to regional in size. Using groundwater flow systems helps establish a relationship between observed water quality in surface water resources and land uses in groundwater recharge areas, and the resulting water quality in groundwater discharge areas and wells (Falkenmark and Allard 1991). Given, that this concept emphasizes the flows of groundwater, some hydrogeologists prefer this concept, particularly for studies of groundwater quality (van der Gun et al. 2011). It also has practical applications in nature and restoration planning in addition to well protection (Batelaan et al. 2003; Puckett et al. 2002). Yet this concept could also be useful in understanding how transboundary groundwater flows relate to issues of depletion and allocation.

3.4.5 **Drivers and Groundwater Units**

Selecting the spatial unit of groundwater resources determines the relevant drivers of groundwater problems at that scale and thus how the groundwater problem is defined. Human activities may be affecting groundwater resources at different lateral extents, depths, with different flow patterns, and different levels of connectivity to other surface or groundwater resources. For example, if agricultural expansion is driving increased pumping from the confined portion of an aquifer it is important to understand that a connected, unconfined aquifer might also be affected. However, simply delineating the aquifer as confined may result in the potential groundwater problems being defined too narrowly. Similarly, pollution of transboundary aquifers may not necessarily result in transboundary transport of the contamination. Thus, defining the pollution as a transboundary problem may be inappropriately broad and negatively affect the relations between the relevant stakeholders without merit.

### 3.5 **Ecosystems Services of Groundwater**

To clearly link the physical characteristics of groundwater with the human and environmental benefits associated with them, this research engages the ecosystems services concept. The ecosystem services concept has been progressively developing for over a century (Mooney et al. 1997); its prevalence in academic literature has been increasing since the late 1970s. The concept was introduced to describe the ‘public benefits’ ecosystems provide and to integrate ecology and economics to explain the consequences of human activities on nature and human welfare (Braat and de Groot 2012; Farber et al. 2006; Foster et al. 2003; Nahlik et al. 2012). Given the economic component of the concept, research around the valuation of nature's services/ecosystem services has also proliferated (Fisher et al. 2009). The numerous initiatives centered on the ecosystems services concept have also led to an abundance of identified functions, classification frameworks, and definitions of ecosystem services (de Groot et al. 2010; Fisher et al. 2009; Wallace 2007). However, the definitions and classifications provided by the Millennium Ecosystems Assessment (MEA) (Millennium Ecosystem Assessment 2005) and Aylward et al. (2005) are used in this research. The MEA states that “[e]cosystem services are the benefits people obtain from ecosystems” (Millennium Ecosystem Assessment 2005) and they are classified as provisioning, regulating, supporting and cultural services. The four classifications are defined as follows:

1. **Provisioning services** are the products people obtain from ecosystems, such as food, fuel, fiber, fresh water, and genetic resources.
2. **Cultural services** are the nonmaterial benefits people obtain from ecosystems through spiritual enrichment, cognitive development, reflection, recreation, and aesthetic experiences.
3. **Regulating services** are the benefits people obtain from the regulation of ecosystem processes, including air quality maintenance, climate regulation, erosion control, regulation of human diseases, and water purification.
4. **Supporting services** are those that are necessary for the production of all other ecosystem services,
such as primary production, production of oxygen, and soil formation (MEA, 2005, Chapter 1: 29).”

3.5.1 Provisioning and Cultural Services of Groundwater

The provisioning and cultural services of groundwater can be broadly grouped into the categories of fresh water for basic needs (drinking water, cooking and hygiene); fresh water for food production; water for energy production; and waters for recreation, health and aesthetic values. Approximately 25% of the global population fulfills their basic needs using groundwater (Machard de Gramont et al. 2011) and 50% use groundwater as their potable water supply (Margat and van der Gun 2013; Mechlem 2003). There are also 1.7 billion people that may intermittently use groundwater as a secondary source because they live in overdrawn river basins. While groundwater is of great importance in arid and semi-arid areas, there are many countries with abundant surface water supplies that use groundwater for their drinking water including Denmark and the Netherlands, which use 100% and 80% respectively. And although groundwater is frequently associated with rural water supply, it is also the source of approximately 50% of municipal water supplies.

Large proportions of groundwater withdrawals support commercial uses for commercial food and energy production. Groundwater irrigates roughly 100 million hectares of land and 43-65% of commercial crops worldwide (Machard de Gramont et al. 2011; Siebert and Burke 2010). Asia and North America make the bulk of agricultural withdrawals, with the United States, India and China the most dependent on groundwater. Also, a rapidly growing portion of withdrawals are for bottled water. In 2014, global bottled water consumption grew more than 6%, totaling more than 74.7 billion gallons (282.8 liters) (Rodwan 2015). Nearly 40% of industrial water withdrawals are from groundwater, a large proportion is for geothermal energy production (Zektser and Everett 2004). Geothermal heating of buildings, greenhouses, fish farms and thermal baths uses groundwater with temperatures ranging between 30° and 90°C. Higher-temperatures can be used to generate electricity. Geothermal energy is projected to grow rapidly as 39 countries could potentially use geothermal groundwater to meet all of their energy needs (Holm et al. 2010).

Groundwater also creates opportunities for recreation; has therapeutic uses and adds to the aesthetic value of various ecosystems. Karstic groundwater formations develop as a result of a unique geologic process in which surface water infiltrates carbonic rock and forms caves, tunnels and crevasses. Recreational activities occurring in these formations such as spelunking are made possible by groundwater. Karstic landscapes are also heralded as some of the most beautiful on earth. Examples include the Plević Lakes in South East Europe and the Karst Mountains and caves in southwest China. Further, groundwater with high mineral content and/or thermal properties is used for balneology and consumed for the purposes of prolonging life. The Katsu Hot Springs of Japan and the mineral waters of Karlovy Vary in the Czech Republic are well known examples.

3.5.2 Regulating and Supporting Services

Regulating and supporting services for groundwater result from the groundwater in and of itself and from the interaction between groundwater and other parts of ecosystems. Two key supporting services of groundwater are its role in soil and land stabilization and its role in sustaining ecosystems. Groundwater also feeds many ecosystems and a sub-set of those are groundwater-dependent including wetlands, terrestrial flora and fauna, springs, rivers and near-shore marine systems. Aquatic and plant species from these ecosystems can be used for human consumption, medicine, fuel and infrastructure. These ecosystem’s levels of groundwater dependence vary based on volume of flow, level, pressure, and quality of groundwater (Margat and van der Gun 2013). Numerous ecosystems worldwide are almost completely dependent on groundwater (i.e. groundwater-dependent ecosystems) and approximately 1.7 billion people live in locations where these ecosystems are being threatened (Aeschbach-Hertig and Gleeson 2012).
Attenuation of contamination is a key regulating service groundwater provides. While the filtration potential of soil is well known, groundwater itself contains microorganisms that can decompose human pathogens and organic wastes (Herman et al. 2001). Consequently, Herman et al. (2001) propose three groundwater biomes that each have particular microbial compositions: (1) shallow, porous aquifers, (2) karst aquifers, and (3) deeper groundwater. Managed aquifer recharge (MAR) techniques can take advantage of these biomes’ regulating services in order to alleviate the consequence of contamination from socio-economic drivers.

Groundwater also provides regulating services with regard to climate. It both contributes to and buffers against global change phenomenon, such as sea-level rise and climate variability, respectively. Groundwater pumping and its subsequent overland discharge has contributed to 12.6 mm sea-level rise between 1900 and 2008 (Konikow 2011) with 0.25 mm (±0.9 mm) of that occurring between 1990 and 2000 (Wada et al. 2012). Groundwater discharge is also expected to make significant contributions to sea level rise in the next 45 years. Although groundwater extraction contributes to sea level rise, the integrity of groundwater resources can also be threatened due to increases in salt water intrusion.

3.5.3 Drivers-Ecosystems Services Feedback Loop So far, I have provided an overview of groundwater resources problems (see 1.2), discussed how human activities can change the natural characteristics of groundwater (see 3.3) and possibly cause these groundwater problems (see 3.3), discussed the ecosystems services groundwater provides to humans by way of these natural characteristic (see 3.5) and the human activities and behaviors that drive groundwater problems (see 3.2). Consequently, this research will explore the relationship between drivers of groundwater problems, characteristics, ecosystem services and definitional issues. This discussion will build upon the approach of Gupta and Pahl-Wostl (Gupta and Pahl-Wostl 2013: 53) which presents “policies as influencing indirect drivers; which shape direct drivers; affecting who gets which [ecosystems] service, how much and for how long; thus, contributing to human well-being.” Additionally, a real-life example is provided in Box 3.1 with the purpose of showing how these various aspects of groundwater problems relate to each other.

Drivers at a specific geographic level (e.g. various human activities or specific hydro(geo)logical phenomena) can lead to global groundwater resource problems, namely over-abstraction, pollution, or reduction or contamination of recharge. However, the delineation of groundwater resources (i.e. the selection of the unit of management) determines how these problems are defined and at what level they are addressed. For example, defining groundwater only with respect to a linkage with a surface water resource may ignore a larger groundwater system and important impacts to that system. Therefore, the definition of the groundwater resource problem may be inappropriately narrow. Nevertheless, once the problems are defined they can be linked to the particular changes in groundwater characteristics occurring as a result, such as reduced storage and/or pressure and reduced discharge to critical groundwater-dependent ecosystems. The changes in character can potentially shift, reduce or eliminate ecosystems services, resulting in unsustainable and non-inclusive outcomes – severe over pumping can limit access to people with sufficient capital to drill deeper wells while simultaneously causing permanent depletion. Since groundwater’s ecosystems services are in fact what allows anthropogenic drivers to exist in the first place, there is a feedback loop, where some shifts in ecosystems services may result in new drivers being introduced into the cycle (e.g. the pumping race).
Box 3.3 Driver Ecosystems Services Feedback Loop in India

Groundwater depletion in India is a well-known and well-documented case of unchecked drivers. Massive and widespread exploitation of groundwater began in the 1970’s. It was driven by a non-water policy intervention aspiring to increase food security – an agricultural energy subsidy. Over the next 30 years, farmers throughout the country extracted groundwater resources and they were well within their rights under the 1882 Indian Easements Act, which allows land owners unrestricted use rights (Aguilar 2011). In this case, the main groundwater problem was over-abstraction, which has occurred to such an extent that it can be measured from space (Rodell et al. 2009).

Comparing the responses of communities in Sangpura and Saurashtra, Gujarat, shows how the changes in groundwater characteristics, ecosystem services and the occurrence of new drivers can result in the feedback loop turning positive or negative. In both these communities, the problem of over-abstraction resulted in loss of storage and pressure. The consequence for ecosystems services was reduced access to groundwater due to dropping groundwater levels and damage to crops due to saltwater intrusion from the coast (Aguilar 2011; Shah 2000). In 2005, Gujarat introduced legislation under the 2005 Model Bill on Groundwater in an effort to counter the drivers of subsidized energy and agricultural intensification. The legislation increased electricity prices and limited institutional credit for digging tube wells. However, new drivers came about in both communities.

In Sangpura, the powerful castes could circumvent the state’s legal restrictions because they had sufficient capital to pay for electricity regardless of increased prices. Thus, not only did groundwater levels continue to fall, but inequities stemming from the caste system were exacerbated (Prakash and Ballabh 2005). In Saurashtra, communities started harvesting and recharging rainwater collected during the monsoon season according to practices from the Hindu sect of Swadhyaya Pariwar (Shah et al. 2012). The state then subsidized check dams that would increase recharge rates and the communities developed rules that restricted pumping and protected recharge areas (Van Steenbergen and Shah 2003). As a result, several communities experienced increased groundwater availability and curbed saline intrusion (Shah 2000; Van Steenbergen and Shah 2003).

In both cases, the original drivers were non-groundwater policy and economic distortion. But new drivers dominated after groundwater problems and degradation of ecosystems services manifested themselves. In both communities, culture and economy became dominant drivers - just in different ways. In Sangpura, culture and economic drivers lead to asymmetrical access, inequity and continued depletion. In Saurashtra, these drivers lead to collective action, development of community-based rules, and restoration of key ecosystems services.

Note: This text is partially based on Conti and Gupta 2015 (see Front Matter).

3.6 Inferences

The discussion of groundwater resources’ characteristics, their ecosystems services and drivers of groundwater change yields three key conclusions regarding how knowledge of groundwater resources can provide insights for governance. First, the characteristics of groundwater are different from surface water. Second, there is a definitional challenge in groundwater governance. Third groundwater governance needs to address the feedback loop that occurs between groundwater’s ecosystems services and drivers of groundwater change in order to achieve sustainable and inclusive development.

Differences between Surface Water and Groundwater

Understanding groundwater’s characteristics of storage, flow, quality and pressure also indicates how differences between surface water and groundwater should be taken into account during governance. Groundwater typically flows slowly and is stored underground for time periods ranging from tens to thousands of years compared to surface water storage periods which are on the order of months to years. Groundwater storage capacity can also be permanently damaged through compression of the subsurface. Additionally, groundwater recharge may occur relatively quickly over weeks or months or can be so slow that it exceeds human time scales. As such, groundwater governance needs to account for long storage times.
and slow recharge through principles that facilitate a multi-decadal outlook. Further, the potential for permanent depletion needs to be directly addressed.

Pressure and geogenic quality are two characteristics that do not have a counterpart in surface water resources. Considering geogenic groundwater quality is an essential element of groundwater governance that is not necessary for surface water resources, if groundwater at a particular location is inadequate for drinking water provision, purification technologies, alternative supplies become critical. If groundwater is in good condition but is at high risk of geogenic contamination, governance frameworks need to facilitate the implementation of targeted management techniques that would prevent contamination and carefully monitor the resources. Maintaining groundwater pressure is an essential component of groundwater accessibility. As such governance needs to facilitate the protection and maintenance of groundwater pressure, particularly in artesian systems where users may become careless due to the seemingly free flowing and abundant groundwater (see 8.2).

**The Definitional Challenge**

Defining groundwater resources in a way that accounts for its key characteristics is critical because it not only determines what is being governed – aquifer, groundwater body or otherwise - but also the specific attributes that will require attention at that scale. But, there are two elements of this challenge. The first is delineation or drawing the boundary of the resource, the second considering the variable and systemic nature of groundwater resources.

In some governance frameworks, the delineation challenge is side stepped by simply appending groundwater resources to surface water resources. An example of this would be a river or lake basin agreement that includes ‘groundwater’ in its scope without (1) specifying whether resources that overlap geographically but do not have a hydrologic link are included or (2) indicating how groundwater resource partially outside boundaries of the surface water basin will be addressed.

In other frameworks, delineation occurs but defines groundwater resources in such a way that their systemic attributes are (1) artificially separated (e.g. into confined and unconfined aquifers or into individual layers of a multi-layered system); (2) the flow and pressure dynamics of the resource are ignored (e.g. non-recharging or artesian aquifers); or (3) the inherent quality of the groundwater is discounted (e.g. saline or thermal groundwater). Thus, subsequent chapters discuss how well existing governance frameworks cope with resource distortion, in practice.

**The Driver-Ecosystems Services Feedback Loop and Sustainable and Inclusive Development**

This chapter’s discussion of drivers shows how humans and nature might directly and indirectly influence groundwater characteristics and therefore impact ecosystems services. Drivers may increase depletion because of services such as agricultural production. Drivers may shift recharge dynamics because of land use changes such as deforestation and desertification. Drivers that increase groundwater abstraction may also cause contamination by mobilizing geogenic contaminants, while industry-related drivers may increase anthropogenic pollution.

Groundwater characteristics determine the physical dynamics that result in the ecosystems services of groundwater. Storage provides regulating and supporting ecosystem services by stabilizing land and soil. Flow contributes base flows to wetlands and rivers. Flow combined with pressure makes water accessible to

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6 Several authors have written about the ‘stagnation’ phenomenon extensively in terms of the negative consequences it has on groundwater modeling. It is often referred to in literature as the aquifer being considered a ‘bath tub.’
humans and ecosystems via springs. Due to its protection from activities at land surface, groundwater is often readily available in potable quality.

Groundwater governance needs to preserve or enhance all ecosystems services to ensure development now and in the future. Yet, when humans take advantage of groundwater’s ecosystems services in a sub-optimal way (i.e. over-utilization, perhaps for the sake of development), they drive changes to these ecosystems. There is a tendency to focus on drivers and impacts on groundwater’s provisioning and cultural services. Yet, as discussed in Section 1.1, in many places, enhancing access to these services is still necessary for sustainable and inclusive development (see 1.1). Groundwater’s supporting and regulating services are also critical in areas experiencing massive subsidence that threatens urban regions or communities with livelihoods threatened by wetland losses. Since many drivers are interconnected and occur across geographic levels, this feedback loop must be addressed in the context of multilevel governance.

**Implications for Groundwater Governance**

Given that sustainable and inclusive development is the guiding norm for this research, maintaining or enhancing ecosystems services of groundwater is critical. In order to do that we must understand drivers and their consequences to the physical dynamics of groundwater. Governance must address these drivers at the appropriate geographic level. But, the groundwater governance frameworks often function at a different spatial scale than groundwater. So, selection of groundwater units and understanding of the advantages and limitation of selecting such units must also be considered in design of groundwater governance frameworks. Further, selection and design of governance principles must fit the most influential drivers at the appropriate geographic level and facilitate interaction between the relevant actors, even outside the water sector. This is particularly important given that many drivers of groundwater problems indicated in Table 3.1 are related to socio-economics, politics, and land use.